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A state-of-the-art two-frequency cross-polarized Rayleigh imaging system was assembled to allow the first fully-resolved four-dimensonal (three space dimensions plus time) non-invasive measurements of conserved scalar mixing in a gaseous turbulent shear flow.

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1. Introduction

This Final Report summarizes the equipment purchased and assembled into the subject measurement system under this Defense University Research Instrumentation Program (DURIP) grant. It also describes how the equipment was used to augment the research being conducted under a separate AFOSR grant dealing with entrainment and mixing in turbulent shear flows, and how the equipment will be used in future research into gaseous mixing in turbulent shear flows.

2. Research Objective of the Instrumentation System

Mixing of a gaseous fuel species with a combustion air stream, and its subsequent combustion under conditions of highly turbulent flow, are the central physical processes that underlie all current and future airbreathing propulsion systems. The engineering objectives that must be addressed in developing improved systems have in recent years focused heavily on such issues as combustion stability and reduction of trace pollutant species emissions. Achieving major improvements in these has become increasingly difficult, as the gains possible from comparatively simple methods for addressing them have become essentially fully exploited. Developing the scientific foundations from which dramatic new gains can be made in these and related areas is one of the objectives of DoD-supported research.

Such major gains require a significant new breakthrough in the ability to understand and effectively model the physical processes involved in turbulent flows and turbulent mixing, and in the consequent nonequilibrium departures that exist in the coupling between molecular mixing and chemical reaction kinetics in turbulent flows. In recent years, a surprising number of important insights have been obtained from a series of experimental studies into these processes, which are suggesting entirely new ways of approaching the description and modeling of turbulent combustion.

The key component to which these recent insights can be attributed is a renewed focus on fundamental experimental measurements of the physical processes at work in turbulent shear flows. Unlike the previous generation of multi-point probe measurements, which were well-suited for studies of the large scale structure of turbulent shear flows, some of the most exciting results being obtained today are from the current generation of high-resolution multi-dimensional spatio-temporal imaging measurements of the fine scale structure of turbulent flows, where the actual molecular mixing and mixing-chemistry coupling occur. Such multi-dimensional imaging measurements inherently produce data that directly give a physical picture of the structure and dynamics of these flow scales, rather than simply giving the projection of this structure onto some very low-dimensional quantity accessible by conventional probe measurements.

The physical picture that this new generation of imaging measurements is offering has revealed a remarkably simple fine scale structure in turbulent flows that, in many ways, mimics the surprising simplicity revealed by the discovery of structure at the large scales in turbulent shear flows some twenty-five years earlier. This comparatively simple fine scale structure had entirely eluded the previous decades of measurements based on single-point and multi-point probes, and was revealed only by the relatively recent development of high-resolution multi-dimensional imaging measurements for turbulent flows. These measurements for the first time offered a direct view onto this fine scale structure. While many of the details remain to be discerned, this emerging physical picture of the small scales of turbulent mixing and combustion is producing a much clearer understanding of the molecular mixing process and the nonequilibrium mixing-chemistry coupling process, as well as their relation to the entrainment rate dictated via the large scale structure of the flow. This understanding has in turn led to some remarkable new ways of modeling the flow, mixing, and chemical reaction processes in turbulent reacting flows, and even new ways of simultaneously simulating these processes.

The measurement system developed under this DURIP grant represents the next step in this process of scientific discovery. It is capable of providing the first-ever simultaneous measurements of the combined spatial and temporal structure of the conserved scalar field $\zeta(\mathbf{x}, t)$, the molecular mixing rate field $\nabla\zeta \cdot \nabla\zeta(\mathbf{x}, t)$, and the underlying vorticity and strain rate fields $\omega(\mathbf{x}, t)$ and $\mathbf{e}(\mathbf{x}, t)$ in a gaseous turbulent shear flow.

3. Description of the Instrumentation System

The instrumentation system assembled under this DURIP grant represents a major extension of our existing planar Rayleigh imaging system (see Fig. 1a). It is designed to allow a set of remarkable new fully-resolved four-dimensional spatio-temporal imaging measurements of the fine scale structure of molecular mixing in gas-phase turbulent shear flows. The central idea is to image four different laser sheets onto four different imaging arrays (see Fig. 1b). Each of these laser sheets is distinguished by a unique combination

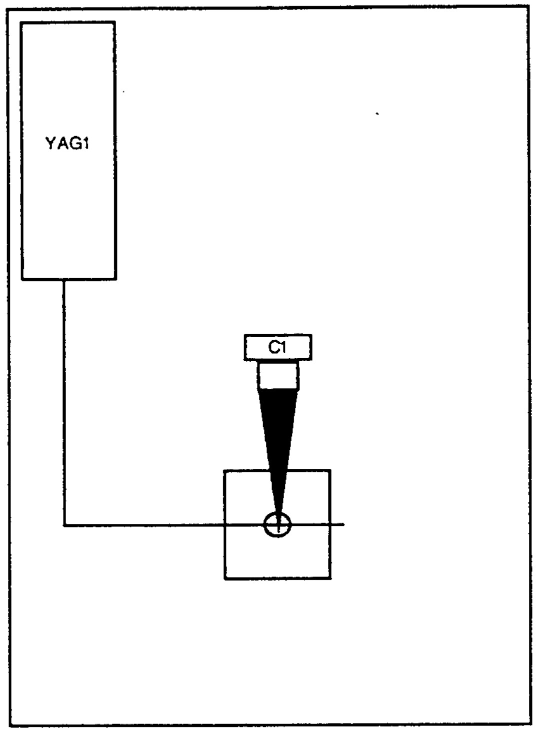

Figure 1a. The previously existing single-plane Rayleigh imaging system.

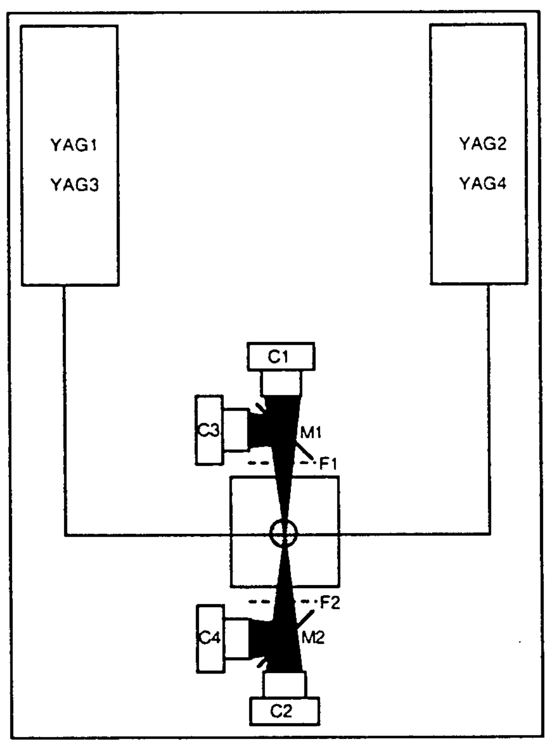

Figure 1b. The new four-plane Rayleigh imaging system.

of frequency and polarization. The laser sheets will be generated by four Nd:YAG lasers, two of which operate in doubled-mode (532 nm) and two of which operate in tripled mode (355 nm). The two sheets at each frequency are arranged to have orthogonal polarizations, by bringing each of the sheets into the flow parallel to each other but propagating at right angles to each other. The sheets are thus brought into the flow from above and deflected 45-degrees downward. The four camera view the sheets through a set of polarization filters and frequency-sensitive mirrors, so that each camera can see only one of the four laser sheets, owing to their unique combination of frequency and polarization.

Two of the four sheets are fired simultaneously and imaged onto their two respective cameras. A few milliseconds later, a delayed pulse fires the other two sheets, which are in turn imaged onto their respective cameras. The net result is that each camera sees only one of the four sheets, and records the Rayleigh scattering within that sheet. Since the sheets are spaced appropriately in the z-direction, the data are simultaneously differentiable in x, y, and z, as well as in time owing to the second two sheets. This allows the mixture fraction field $\zeta(\mathbf{x},t)$ as well as the molecular mixing rate field $\nabla\zeta\cdot\nabla\zeta(\mathbf{x},t)$ to be determined. Moreover, from the simultaneous space and time differentiable data, the underlying vorticity and strain rate fields $\omega(\mathbf{x},t)$ and $\mathbf{e}(\mathbf{x},t)$ can also be determined via the scalar imaging velocimetry technique.

4. Listing of all Equipment Acquired

A complete list of all equipment purchased to assemble this unique instrumentation system is attached on the following pages. All major aspects of the equipment purchased conform to the list in the original proposal. This includes the YAG laser systems and associated optics and computer interfaces. The list shows all individual items purchased, including individual smaller equipment items required to assemble and set up the larger equipment items into a functioning system.

QTY.	ITEM DESCRIPTION	MODEL #	MANUFACTURER	DATE	AMOUNT
3	OSCILLATOR/AMPLIFIER ND/YAG LASER, 1250mJ AT 1064NM WITH 70% GAUSSIAN FIT WITH HARMONIC GENERATOR AND 532NM AND 335 NM DICHROIC BEAM SPLITTERS AND WAVEPLATES	PRO-230-10	SPECTRA PHYSICS	4/3/98	209288.05
3	CAMERA SYSTEM: TE/CCD 512X512 THERMOELECTRIC AND AIR COOLED CCD DETECTOR 2 WITH LUMOGEN UV COATING AND 1 WITHOUT IT, ST-138S CONTROLLER, AND WINVIEW SOFTWARE	TE/CCD 512X512	PRINCETON INSTR.	4/10/98	49124.65
1	REFURBISHED 20 W ARGON ION LASER	Beamlok 2080-20S	SPECTRA PHYSICS	5/1/98	42500.00
1	DIGITAL I/O ISA: PARALLEL BOARD	CIO-D1024	COMPUTER BOARDS	6/1/98	67.20
1	PCI-GPIB BOARD	PCI-GPIB	COMPUTER BOARDS	6/1/98	269.00
1	19" MONITOR	1200HS	DELL	6/30/98	609.00
1	400 MHZ PENTIUM I PROCESOR W/512K CACHE	OPTIPLEX GX1	DELL	6/30/98	2978.94
1	MULTICONTROLLER SOFTWARE		PRINCETON INSTR.	7/31/98	2800.00
1	SOFTWARE DLL'S FOR PROGRAMMING		PRINCETON INSTR.	7/31/98	1200.00
1	DIGITAL DELAY GENERATOR	DG535	STANFORD RESEARCH	4/14/98	3522.54
1	6-1" PVC TEC, 6-1X1/2 BUSHING, 4-1/2X6 NIPPLE, 4-1/2X3 NIPPLE, 8-1/2" ELL, 8-1/2" TEC, 4-1/2X8" NIPPLE, 20-1/2 PVC, 1 PVC GLUE, 1 PVC PRIME, 8-1/2" BALL VALVES PVC SCH 80	MISC.	J. O. GALLOUP	6/1/98	175.06
1	3/8" BENDER	4A521	W W GRAINGER	6/18/98	49.12
2	MALE CONNECTOR (3/8-1/2)	SS-600-1-2	H. E. LENNON	6/18/98	18.20
8	MALE ELBOW CONNECTOR (3/8-1/8)	SS-600-2-1	H. E. LENNON	6/18/98	96.80
8	UNION ELBOW 3/8"	SS-600-9	H. E. LENNON	6/18/98	113.25
8	INSERT 3/8"	SS-605-5	H. E. LENNON	6/18/98	13.60
4	VISI-FLOAT METERS 2" SCALE VFA	DW812	DAVIS INSTRUMENT	6/25/98	125.55
1	DIGITAL DELAY GENERATOR	DG535	STANFORD RESEARCH	7/30/98	3875
1	200 FT 3/8" VINYL TUBE AND CONNECTORS		STADIUM HARDWARE	7/30/98	74.42
1	BUSHINGS, PVC		J. O. GALLOUP	7/30/98	10.24
2	NITROGEN REGULATORS	VTS450D-580	M-STORES GASES	7/27/98	232.60
1	HIGH VACUUM PUMP	9950K21	MCMASTER	9/24/98	1278.84
1	ACHROMATIC DOUBLER	23-9723	COHERENT INC.	5/11/98	327.06
1	ACHROMATIC DOUBLER	23-9749	COHERENT INC.	5/11/98	275.73
2	COLOR GLASS FILTER	26-5579	COHERENT INC.	5/11/98	156.98
2	COLOR GLASS FILTER	26-4283	COHERENT INC.	5/11/98	76.48
1	POLARIZING BEAMSPLITTER	44-4430	COHERENT INC.	5/11/98	271.70
4	OPTICAL CARRIER	07-OCP-505	MELLES GRIOT	11/30/98	448.01

2	OPTICAL CARRIER	07-OCP-501	MELLES GRIOT	11/30/98	138.48
1	STANDARD ROD	07-DUS-S13	MELLES GRIOT	11/30/98	173.09
6	ADJUSTABLE CYLINDRICAL LENS HOLDER	07-LHC-003	MELLES GRIOT	11/30/98	641.47
6	TRANSLATIONAL STAGE	07-TCS-515	MELLES GRIOT	11/30/98	2596.40
6	OPTICAL RAIL	07-ORP-003	MELLES GRIOT	11/30/98	665.90
1	LENS	RCC-40-25.4-25.4-C	CVI LASER CORPT.	3/12/98	488.88
1	LENS	RCC-40-25.4-381.4-C	CVI LASER CORPT.	3/12/98	383.05
1	LENS	RCC-40-25.4-381.4-UV	CVI LASER CORPT.	3/12/98	423.37
1	LENS	RCC-40-25.4-25.4-UV	CVI LASER CORPT.	3/12/98	532.25
1	INSTALLATION OF CIRCUITS IN ROOM 2250				125.52
1	PLATFORM	M-300-P	NEWPORT CORP.	2/12/98	157.23
1	FINE POSITIONER	M-32A	NEWPORT CORP.	2/12/98	94.91
2	ADJUSTABLE POST	ALM-2	NEWPORT CORP.	2/12/98	554.13
22	BASIC TRANSLATIONAL STAGE	M-TSK-ID	NEWPORT CORP.	2/12/98	2604.78
1	SCREW KIT	M-SK-M6A	NEWPORT CORP.	2/12/98	44.10
15	HOLDER	M-VPH-2	NEWPORT CORP.	2/12/98	179.76
15	POST	M-SP-2	NEWPORT CORP.	2/12/98	89.89
5	POST	M-SP-3	NEWPORT CORP.	2/12/98	34.70
5	HOLDER	M-VPH-3	NEWPORT CORP.	2/12/98	64.62
7	COMPAT ROTATION STAGE	M-RSP-1	NEWPORT CORP.	2/12/98	760.54
2	PRISM TABLE	PT-1	NEWPORT CORP.	2/12/98	129.23
1	MIRROR BEAMSPLITTER	SL8ABD	NEWPORT CORP.	2/12/98	1396.63
1	MIRROR BEAMSPLITTER	SL8ABD	NEWPORT CORP.	2/1/99	-1386.05
1	SCREW SET	M-SK-M4A	NEWPORT CORP.	2/12/98	44.03
2	ADJUSTABLE LENS HOLDER	ALM-4	NEWPORT CORP.	4/12/98	635.30
3	MIRROR HOLDER	M-MM2-1A	NEWPORT CORP.	4/12/98	169.60
1	PRECISION GIMBAL	605-2-DM	NEWPORT CORP.	9/12/98	700.75
1	MIRROR BEAMSPLITTER	SL8ABD	NEWPORT CORP.	12/17/98	1398.25
1	MIRROR BEAMSPLITTER	SL8ABD	NEWPORT CORP.	2/1/99	-1386.05
2	ADJUSTABLE CYLINDRICAL LENS HOLDER	07-LHC-003	MELLES GRIOT	12/14/98	221.75
2	LENS	BSP-35-3037	CVI LASER CORPT.	12/15/98	2454.50
2	TRIPLET LENS	UVAP-125-50-355	CVI LASER CORPT.	1/11/99	3618.65
1	REFRIGERATOR/CIRCULATOR SYSTEM	CST25	NESLAB INSTR. INC.	2/5/99	2106.00
4	QUICK CONNECTOR	SS-QC8-D-810 1/2"	H. E. LENNON	2/10/99	120.29
4	QUICK CONNECTOR	SS-QC8-B-810 1/2"	H. E. LENNON	2/10/99	155.12
2	QUICK CONNECTOR	SS-QC6-D-600 3/8"	H. E. LENNON	2/10/99	134.33
2	QUICK CONNECTOR	SS-QC6-B-600 3/8"	H. E. LENNON	2/10/99	65.65
1	PRECISION GIMBAL	605-2-DM	NEWPORT CORP.	2/11/99	715.30
1	PRECISION GIMBAL	605-2-DM	NEWPORT CORP.	2/17/99	715.30
1	LENS	UVAP-80-50-355	CVI LASER CORPT.	5/17/99	3618.85
1	45 ADAPTER	53-2853	COHERENT INC.	3/4/99	27.00

1	PRECISE MIRROR MOUNT	53-2218	COHERENT INC.	3/4/99	51.00
1	INSTALLATION OF CIRCUITS IN ROOM 2250			5/24/99	409.59
1	LENS	UVAP-80-50-355	CVI LASER CORPT.	3619.85	3619.85
4	LASER MIRROR 45 (532 NM)	16-MLB-153	MELLES GRIOT	12/5/98	720.00
4	LASER MIRROR 45 (355 NM)	16-MLB-133	MELLES GRIOT	12/5/98	920.00
1	POLARIZING BEAMSPLITTER	03-PBS-127	MELLES GRIOT	12/5/98	438.00
2	OPTICAL RAIL (2M)	07-ORP-011	MELLES GRIOT	12/5/98	830.00
22	OPTICAL RAIL CARRIER	07-OCP-503	MELLES GRIOT	12/5/98	1804.00
2	TRANSLATIONAL STAGE	07-TSS-507-05	MELLES GRIOT	12/5/98	850.00
1	VECTOR PYROELECTRIC DETECTOR	PIID50	SCIENTECH	2/12/99	1595.00
1	A/D POWER METER	H310	SCIENTECH	2/12/99	995.00
1	YAG LENS	VX50	SCIENTECH	2/12/99	295.00
TOTAL					**358912.96**